Tuberculosis Vaccine with Improved Efficacy

Description

The present invention relates to novel recombinant vaccines providing protective immunity especially against tuberculosis.

Tuberculosis (TB) caused by Mycobacterium tuberculosis remains a significant global problem. It is estimated that one third of the world's population is infected with M.tuberculosis (Kochi, 1991). In many countries the only measure for TB control has been vaccination with M.bovis bacille Calmette-Guérin (BCG). The overall vaccine efficacy of BCG against TB, however, is about 50 % with extreme variations ranging from 0 % to 80 % between different field trials (Roche et al., 1995). Thus, BCG should be improved, e.g. by genetic engineering, to provide a vaccine for better TB control (Murray et al., 1996; Hess and Kaufmann, 1993). The widespread emergence of multiple drug-resistant M.tuberculosis strains additionally underlines the urgent requirement for novel TB vaccines (Grange, 1996).

M.tuberculosis belongs to the group of intracellular bacteria that replicate within the phagosomal vacuoles of resting macrophages, thus protection against TB depends on T cell-mediated immunity (Kaufmann, 1993). Several studies in mice and humans, however, have shown that Mycobacteria stimulate antigen-specific, major histocompatibility complex (MHC) class II- or class I-restricted CD4 and CD8 T cells, respectively (Kaufmann, 1993).

The important role of MHC class I-restricted CD8 T cells was convincingly demonstrated by the failure of β2-microglobulin (β2m) deficient mice to control experimental M.tuberculosis infection (Flynn et al., 1993). Because these mutant mice lack MHC class I, functional CD8 T cells cannot develop. In contrast to M.tuberculosis infection, β2m-deficient mice are capable of controlling certain infectious doses of the BCG vaccine strain (Flynn et al., 1993; Ladel et al., 1995). Furthermore, BCG vaccination of β2m-deficient mice prolonged survival after subsequent M.tuberculosis infection whereas BCG-immunized C57BL/6 resisted TB (Flynn et al., 1993). This differential CD8 T cell dependency between M.tuberculosis and BCG may be explained as

follows: M.tuberculosis antigens gain better access to the cytoplasm than antigens from BCG leading to more pronounced MHC class I presentation (Hess and Kaufmann, 1993). Consequently, a more effective CD8 T cell response is generated by M.tuberculosis. This notion was recently supported by increased MHC class I presentation of an irrelevant antigen, ovalbumin, by simultaneous M.tuberculosis, rather than BCG, infection of antigen presenting cells (APC) (Mazzaccaro et al., 1996).

Secreted proteins of M.tuberculosis comprise a valuable source of antigens for MHC class I presentation. Recently, a DNA vaccine encoding the secreted antigen Ag85A elicited MHC class I-restricted CD8 T cell responses in mice which may contribute to defence against TB (Huygen et al., 1996). In general, evidence is accumulating that immunization with secreted protein antigens of M.tuberculosis induce some protection against TB in guinea pigs and mice (Horwitz et al., 1995; Andersen, 1994). An important goal towards the development of improved TB vaccines based on BCG, therefore, is to augment the accessibility of secreted BCG-specific antigens to the cytoplasm of infected APC. Subsequent delivery of peptides derived from these secreted proteins into the MHC class I presentation pathway may potentiate the already existing BCG-specific immune response for preventing TB.

The phagolysosomal escape of L.monocytogenes represents a unique mechanism to facilitate MHC class I antigen presentation of listerial antigens (Berche et al., 1987; Portnoy et al., 1988). Listeriolysin (Hly), a pore-forming sulfhydryl-activated cytolysin, is essential for the release of L.monocytogenes microorganisms from phagolysosomal vacuoles into the cytosol of host cells (Gaillard et al., 1987; Portnoy et al., 1988). This escape function was recently transferred to Bacillus subtilis and to attenuated Salmonella ssp. strains (Bielecki et al., 1991; Gentschev et al., 1995; Hess and Kaufmann, 1997). Hly expression by an asporogenic B.subtilis mutant strain or in Salmonella ssp. results in bacterial escape from the phagolysosome into the cytosol of J774 macrophage-like cells (Bielecki et al., 1991; Gentschev et al., 1995; Hess and Kaufmann, 1997).

WO 99/101496 and Hess et al. (1998) disclose recombinant Mycobacterium bovis strains that secrete biologically active Listeriolysin fusion proteins. These M.bovis strains have been shown to be effective vaccines against TB in

several animal models.

According to the present invention Hly was expressed in urease-deficient BCG strains. These urease-deficient BCG strains exhibit an increased Hly activity in phagosomes and in turn improved pore formation in the endosomal membranes leading to superior immunoprotectivity. Further, urease-deficient BCG-Hly strains are involved in apoptotic processes which may contribute to an enhanced immune protection. Thus, the urease-deficient BCG strains have an even further improved vaccine capacity. Further, it was surprisingly found that urease-deficient BCG strains exhibit an increased safety profile compared to BCG parent strains and thus are particularly suitable for the vaccination of immunodeficient patients.

A first aspect of the present invention is a bacterial cell, particularly a Mycobacterium cell which is urease-deficient and comprises a recombinant nucleic acid molecule encoding a fusion polypeptide comprising (a) at least one domain from a polypeptide, wherein said polypeptide domain is capable of eliciting an immune response in a mammal, and (b) a phagolysosomal escape domain. It is preferred that the cell is capable of expressing the nucleic acid molecule of the invention. More preferably, the cell is capable of secreting the fusion polypeptide and/or of providing it in a form suitable for MHC class I-restricted antigen recognition.

The bacterial cell of the invention is a urease-deficient cell, e.g. a gram-negative or a gram-positive bacterial cell, preferably a Mycobacterium cell. The urease-deficiency may be achieved by partially or completely inactivating one or several cellullar nucleic acid molecules which code for a urease subunit, particularly ureA encoding for urease subunit A, ureB coding for urease subunit B and/or ureC coding for urease subunit C. The sequences of ureA, ureB and ureC in Mycobacteria, particularly M.bovis and M.tuberculosis and the proteins encoded thereby are described by Reyrat et al. (1995) and Clemens et al. (1995), which are incorporated herein by reference.

Preferably the urease-deficient bacterial strain is obtained by deletions and/or insertions of one or several nucleotides in urease subunit - coding nucleic acid sequences and/or their expression control sequences. Deletions and/or insertions may be generated by homologous recombination, transposon

insertion or other suitable methods.

In an especially preferred embodiment the ureC sequence is inactivated, e.g. by constructing a suicide vector containing a ureC gene disrupted by a selection marker gene, transforming the target cell with the vector and screening for selection marker-positive cells having a urease negative phenotype as described by Reyrat et al. (1995).

The cell of the invention is preferably an M.bovis cell, a M.tuberculosis cell, particularly an attenuated M.tuberculosis cell or other Mycobacteria, e.g. M.microti, M.smegmatis, M.canettii, M.marinum or M.fortuitum or Mycobacteria as described by Reyrat et al. (1995).

The Mycobacterium cell of the invention comprises a recombinant nucleic acid molecule, e.g. the nucleic acid molecule in SEQ ID No.1. This nucleic acid molecule comprises a signal peptide coding sequence (nucleotide 1 - 120), a sequence coding for an immunogenic domain (nucleotide 121 - 153), a peptide linker coding sequence (nucleotide 154 - 210), a sequence coding for a phagolysosomal domain (nucleotide 211 - 1722), a further peptide linker coding sequence (nucleotide 1723 - 1800) and a sequence coding for a random peptide (nucleotide 1801 - 1870). The corresponding amino acid sequence is shown in SEQ ID No.2.

The nucleic acid contains at least one immunogenic domain from a polypeptide. The immunogenic domain may be derived from an organism of the genus Mycobacterium, preferably from Mycobacterium tuberculosis or from Mycobacterium bovis. This domain has a length of at least 6, preferably of at least 8 amino acids. The immunogenic domain is preferably a portion of a native Mycobacterium polypeptide. However, within the scope of the present invention is also a modified immunogenic domain, which is derived from a native immunogenic domain by substituting, deleting and/or adding one or several amino acids.

The immunogenic domain is however not restricted to Mycobacterium antigens and can be selected from autoantigens, tumor antigens and pathogen antigens such as virus antigens, parasite antigens, bacterial antigens in general and immunogenic fragments thereof. Specific examples for suitable tumor antigens

are human tumor antigens such as the p53 tumor suppressor gene product (Houbiers et al., 1993) and melanocyte differentiation antigens, e.g. Melan-A/MART-1 and gp100 (van Elsas et al., 1996). Specific examples for suitable virus antigens are human tumor virus antigens such as human papilloma virus antigens, e.g. antigens E6 and E7 (Bosch et al., 1991), influenza virus antigens, e.g. influenza virus nucleoprotein (Matsui et al., 1995; Fu et al., 1997) or retroviral antigens such as HIV antigens, e.g. the HIV-1 antigens p17, p24, RT and Env (Harrer et al., 1996; Haas et al., 1996). Specific examples for suitable parasite antigens are Plasmodium antigens such as liver stage antigen (LSA-1), circumsporozoite protein (CS or allelic variants cp26 or cp29), thrombospondin related amonymous protein (TRAP), sporozoite threonine and asparagine rich protein (STARP) from Plasmodium falciparum (Aidoo et al., 1995) and Toxoplasma antigens such as p30 from Toxoplasma gondii (Khan et al., 1991; Bulow and Boothroyd, 1991). Specific examples for suitable bacterial antigens are Legionella antigens such as Major secretary protein from Legionella pneumophila (Blander and Horwitz, 1991).

The immunogenic domain is capable of eliciting an immune response in a mammal. This immune response can be a B cell-mediated immune response. Preferably, however, the immunogenic domain is capable of eliciting a T cell-mediated immune response, more preferably a MHC class I-restricted CD8 T cell response.

The domain capable of eliciting an immune response is more preferably selected from immunogenic peptides or polypeptides from M.bovis or M.tuberculosis or from immunogenic fragments thereof. Specific examples for suitable antigens are Ag85B (p30) from M.tuberculosis (Harth et al., 1996), Ag85B (α-antigen) from M.bovis BCG (Matsuo et al., 1988), Ag85A from M.tuberculosis (Huygen et al., 1996) and ESAT-6 from M.tuberculosis (Sorensen et al., 1996, Harboe et al., 1996 and Andersen et al., 1995). More preferably, the immunogenic domain is derived from the antigen Ag85B. Most preferably, the immunogenic domain comprises the sequence from aa.41 to aa.51 in SEQ ID No.2.

The recombinant nucleic acid molecule according to the present invention further comprises a phagolysosomal escape domain, i.e. a polypeptide domain which provides for an escape of the fusion polypeptide from the

phagolysosome into the cytosol of mammalian cells. Preferably, the phagolysosomal escape domain is a Listeria phagolysosomal escape domain, which is described in US 5,733,151, herein incorporated by reference. More preferably, the phagolysosomal escape domain is derived from the organism L.monocytogenes. Most preferably, the phagolysosomal domain is encoded by a nucleic acid molecule selected from: (a) a nucleotide sequence comprising nucleotides 211 - 1722 as shown in SEQ ID No.1, (b) a nucleotide sequence which encodes for the same amino acid sequence as the sequence from (a), and (c) a nucleotide sequence hybridizing under stringent conditions with the sequence from (a) or (b).

Apart from the nucleotide sequence depicted in SEQ ID No.1 the present invention also comprises nucleic acid sequences hybridizing therewith. In the present invention the term "hybridization" is used as defined in Sambrook et al. (Molecular Cloning. A laboratory manual, Cold Spring Harbor Laboratory Press (1989), 1.101-1.104). In accordance with the present invention the term "hybridization" is used if a positive hybridization signal can still be observed after washing for one hour with 1 X SSC and 0.1 % SDS at 55°C, preferably at 62° C and more preferably at 68°C, particularly for 1 hour in 0.2 X SSC and 0.1 % SDS at 55°C, preferably at 62°C and more preferably at 68°C. A sequence hybridizing with a nucleotide sequence as per SEQ ID No.1 under such washing conditions is a phagolysosomal escape domain encoding nucleotide sequence preferred by the subject invention.

A nucleotide sequence encoding a phagolysosomal escape domain as described above may be directly obtained from a Listeria organism or from any recombinant source e.g. a recombinant E.coli cell containing the corresponding Listeria nucleic acid molecule or a variant thereof as described above.

Preferably, the recombinant nucleic acid molecule encoding for a fusion polypeptide contains a signal peptide encoding sequence. More preferably, the signal sequence is a signal sequence active in Mycobacteria, preferably in M.bovis, e.g. a native M.bovis signal sequence. A preferred example of a suitable signal sequence is the nucleotide sequence coding for the Ag85B signal peptide which is depicted in SEQ ID No.1 from nucleotide 1 to 120.

Further, it is preferred that a peptide linker be provided between the immunogenic domain and the phagolysosomal escape domain. Preferably, said peptide linker has a length of from 5 to 50 amino acids. More preferably, a sequence encoding a linker as shown in SEQ ID No.1 from nucleotide 154 to 210 or a sequence corresponding thereto as regards the degeneration of the genetic code.

The nucleic acid may be located on a recombinant vector. Preferably, the recombinant vector is a prokaryotic vector, i.e. a vector containing elements for replication or/and genomic integration in prokaryotic cells. Preferably, the recombinant vector carries the nucleic acid molecule of the present invention operatively linked with an expression control sequence. The expression control sequence is preferably an expression control sequence active in Mycobacteria, particularly in M.bovis. The vector can be an extrachromosomal vector or a vector suitable for integration into the chromosome. Examples of such vectors are known to the man skilled in the art and, for instance, given in Sambrook et al. supra.

In a further aspect of the present invention a urease-deficient bacterial cell e.g. a Mycobacterium cell, preferably an M.bovis cell is provided which comprises at least one nucleic acid molecule encoding a phagolysosomal escape peptide or polypeptide. Even if the phagolysosomal escape peptide or polypeptide is not fusioned with an antigen, a surprising improvement of the immunogenic properties is found.

The recombinant bacterial cell which is provided according to this further ascpect of the present invention may contain at least one further recombinant, e.g. heterologous nucleic acid molecule encoding a peptide or polypeptide capable of eliciting an immune response in a mammal. Said further immunogenic peptide or polypeptide may be selected from Mycobacterium antigens or, in a wider sense, from autoantigens, tumor antigens, pathogen antigens and immunogenic fragments thereof. The nucleic acid molecule coding for the further peptide or polypeptide may be situated on the same vector as the fusion gene. However, it may, for example, also be situated on a different plasmid, independently of the fusion gene, or be chromosomally integrated.

Surprisingly, it was found that a Mycobacterium cell according to the present invention has an intracellular persistence in infected cells, e.g. macrophages, which is equal or less than the intracellular persistence of a corresponding native Mycobacterium cell which does not contain the recombinant nucleic acid molecule.

The present invention also refers to a pharmaceutical composition comprising as an active agent a cell as defined above, optionally together with pharmaceutically acceptable diluents, carriers and adjuvants. Preferably, the composition is a living vaccine suitable for administration to a mammal, preferably a human. The actually chosen vaccination route depends on the choice of the vaccination vector. Administration may be achieved in a single dose or repeated at intervals. The appropriate dosage depends on various parameters such as the vaccinal vector itself or the route of administration. Administration to a mucosal surface (e.g. ocular, intranasal, oral, gastric, intestinal, rectal, vaginal or urinary tract) or via the parenteral route (e.g. subcutaneous, intradermal, intramuscular, intravenous or intraperitoneal) might be chosen.

Further, the present invention pertains to a method for preparing a recombinant bacterial cell as defined above. According to the first aspect, this method comprises the steps of (i) providing a urease-deficient bacterial cell, particularly a Mycobacterium cell, (ii) inserting a recombinant nucleic acid molecule into said bacterial cell, said nucleic acid molecule encoding a fusion polypeptide comprising (a) at least one domain from a polypeptide wherein said domain is capable of eliciting an immune response in a mammal and (b) a phagolysosomal escape domain, and (iii) cultivating the cell obtained according to step (ii) under suitable conditions. Preferably, a cell is obtained which is capable of expressing said nucleic acid molecule. More preferably, the cell is an M.bovis cell.

According to the further aspect, this method comprises the step of (i) providing an urease-deficient bacterial cell, particularly a Mycobacterium cell, (ii) inserting a recombinant nucleic acid molecule into said bacterial cell, said nucleic acid molecule encoding a phagolysosomal escape peptide or polypeptide, and (iii) cultivating the cell obtained according to (ii) under suitable conditions.

If desired, the method of the present invention comprises inserting at least one further recombinant nucleic acid molecule into the bacterial cell, said further recombinant nucleic acid molecule encoding a peptide or polypeptide capable of eliciting an immune response in a mammal.

Finally, the present invention relates to a method for the preparation of a living vaccine comprising formulating the recombinant cell in a pharmaceutically effective amount with pharmaceutically acceptable diluents, carriers and/or adjuvants.

Due to the high safety of urease-deficient bacterial cells, which was demonstrated in two different animal models (Example 3), the living vaccine of the present invention is particularly suitable for administration to immunodeficient subjects, e.g. subjects suffering from an HIV infection or subjects which are treated with immunosuppressive drugs. In an especially preferred embodiment, the living vaccine of the present invention is used as a tuberculosis vaccine for immunodeficient subjects.

In a further preferred embodiment, the living vaccine is used as a tumor vaccine, e.g. as a vaccine against superficial bladder cancer. In a still further preferred embodiment of the invention, the living vaccine is used in the veterinary field, e.g. as a vaccine against listeriosis, paratuberculosis or bovine tuberculosis.

The invention will be further illustrated by the following figures and sequence listings.

Fig.1: shows the protective capacity of rBCG ureC Hly in the aerosol model of murine tuberculosis. BALB/c mice were immunized i.v. with $1x10^6$ CFU rBCG ureC Hly, BCG P ureC or native BCG "Pasteur". 120 days post vaccination animals were challenged with H37Rv (200 organism/lung) via aerosol. Bacterial load in infected organs (spleen and lung) was assessed 30, 60 and 90 days post challenge. Each bar represents 10 animals.

Fig. 2: shows the amount of microorganisms in the lung (Fig. 2a) or in the spleen (Fig. 2b). Rag1-/- mice were infected with the BCG parental

strain (wt) or the rBCG ureC Hly strain (urea-Hly). Bacterial load of the infected organ was assessed 30, 60 and 90 days post infection.

Fig. 3: shows the survival rate of SCID mice infected with BCG "Pasteur" and rBCG delta ureC Hly.

SEQ ID No.1: shows the nucleotide sequence of a nucleic acid molecule according to the present invention.

SEQ ID No.2: shows the corresponding amino acid sequence of the nucleic acid molecule of SEQ ID No.1.

Example 1 Production of urease-deficient BCG Hly strains and tests in a mouse model

1. Inactivation of the urease activity of BCG delta ureC.

In order to improve the protective capacity of a BCG strain containing the Hly protein (rBCG-Hly), the urease activity was deleted.

To obtain a urease-deficient mutant, Reyrat et al. constructed a suicide vector containing a ureC gene disrupted by a kanamycin marker (the aph gene). Two micrograms of this construct were linearized with Sac I and electroporated into M. bovis BCG. Kanamycine resistant transformants were screened for urease negative phenotype (cf. Reyrat et al., 1995).

2. Construction of the mycobacterial E. coli shuttle expression vector pMV306:Hly.

To transfer the phagosomal escape function (mediated by Hly of L. monocytogenes EGD Sv 1/2a), to BCG Pasteur (1173 P_3) delta ureC, an E. coli-mycobacterial shuttle vector was used. The integrative plasmid pMV306, a precursor of vector pMV361, allows stable chromosomal expression of Hly.

A pILH-1-derived 1.7-kb PstI DNA fragment coding for an hly-hlyA (E. coli pHly152-specific hemolysin A) ORF was inserted into PstI site of

plasmid pAT261. This resulting gene fusion codes for the expression of secreted proteins directed to the supernatant by the BCG-specific Ag85B signal peptide. The construct was termed pAT261:Hly and its XbaI-SalI DNA expression cassette under transcriptional control of the hsp60 mycobacterial promoter was subsequently used for insertion into the parental pMV306 vector resulting in the construct pMV306:Hly. The DNA sequence of the hly-specific insertion sites in both mycobacterial expression plasmids was analyzed. The mature Hly fusion protein putatively consists of 30 aa at the N terminus and 52 aa at the C-terminal part of the fusion that partially belong to HlyA of E. coli.

3. Protective capacity in the mouse model

The expression vector pMV306:Hly was transformed into an urease deficient BCG strain pasteur (BCG P ureC). The resultant strain was designated rBCG ureC Hly. The protective capacity of this urease-deficient mycobacterial strain compared to parental BCG Pasteur and BCG Pasteur ureC in a model of murine tuberculosis is shown in Figure 1. Surprisingly, it was found that rBCG ureC Hly induced improved protection already at early time points (day 30 p.c.) which lasted for the entire observation period (until day 90).

A further long-term protection experiment with rBCG ureC Hly was performed. BALB/c mice were i.v. vaccinated with rBCG ureC Hly, rBCG-Hly or parental BCG and aerosol challenged at day 120 p.i. with *M. tuberculosis* H37Rv. RBCG-Hly and parental BCG induced comparable protection against *M. tuberculosis* H37Rv by day 90. In strong contrast, the rBCG ureC Hly induced improved protection already at early times points beginning at day 30 p.c. Furthermore, this enhanced protection lasted for the entire period of observation and revealed a reduction of *M. tuberculosis* H37Rv load in lung at day 90 p.c. of more than 2 log CFU compared to naive mice, and of more than 1 log CFU compared to mice vaccinated with parental BCG.

Similar results were obtained after challenge with the clinical isolate *M. tuberculosis* Beijing. BALB/c mice were i.v. immunised with rBCG ureC Hly, BCG-Hly or parental BCG and aerosol challenged at day 120 p.i.

with *M. tuberculosis* Beijing. Vaccination with BCG ureC Hly induced an improved protection against *M. tuberculosis* Beijing already at early time points (day 30) and lasting for the entire period of observation until day 90 p.c. Compared to vaccination with parental BCG, vaccination with rBCG ureC Hly led to a reduction in the lung of 1 log CFU *M. tuberculosis* Beijing.

Example 2 Long-term protection against *M. tuberculosis* H37Rv in guinea-pigs

Since mice are relatively resistant to *M. tuberculosis* infection guinea-pigs as a more susceptible animal model were used to test for vaccination capacity of rBCG ureC Hly. Guinea-pigs were subcutaneously immunised with the respective mycobacterial vaccine strain, rBCG ureC Hly or parental BCG, and weight gain as well as CFU were monitored after aerosol challenge with *M. tuberculosis* H37Rv. Guinea-pigs immunised with rBCG ureC Hly showed similar weight gain than animals vaccinated with the parental BCG strain up to day 120, whereas non-vaccinated animals clearly suffered from TB as indicated by the failure of body weight gain.

Visual examination of lung and spleen prior to CFU analysis showed that tubercles on the surface of both organs from BCG-immunised guinea pigs were much larger and more numerous than those from BCG ureC Hly-vaccinated animals.

Example 3 Saftey evaluation of BCG ureC Hly

Rag1-/-mice deficient in T- and B-cells were infected with 10^6 microorganisms of the BCG parental strain (wt) or the rBCG ureC Hly strain. The presence of microorganisms in lung and spleen was monitored. Significantly reduced CFU of rBCG ureC Hly were observed in the lung (Fig. 2a). In the spleen, slightly reduced CFU were observed after infection with rBCG ureC Hly compared to infection with parental BCG (Fig. 2b).

Further, the safety of BCG ureC Hly was tested in immunodeficient SCID mice.

For this purpose, SCID mice were intravenously innoculated with 10^7-10^8 microorganisms of rBCG ureC Hly or the parental BCG strain. Whereas SCID mice innoculated with the parental strain died until day 25 p.i., mice innoculated with rBCG ureC Hly survived until day 150 p.i. (Fig. 3).

These experiments demonstrated that BCG ureC Hly has a higher safety compared to the parental BCG strain.

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